

**We claim:**

1. **A monolithically integrated vertical PIN photodiode** formed in biCMOS technology and having a substantially planar surface (30) facing the light ( $h\nu$ ) and having a back side (31) and anode terminals (A1, A2) via p regions (20, 21) on a topside of the photodiode, wherein an i-zone of the PIN photodiode is formed by
  - (a) a combination of a first  $p^-$  epitaxial layer (10,  $d_{10}$ ) with a thickness of substantially  $15\mu\text{m}$  at most and having a dopant concentration of less than  $5 \cdot 10^{14} \text{ cm}^{-3}$ , wherein the  $p^-$  epitaxial layer is located on a p substrate (11), in particular, a highly doped p-substrate;
  - (b) a slightly doped  $n^-$  epitaxial layer (9) adjacent to the first layer (10) and having a dopant concentration in a range of substantially  $10^{14} \text{ cm}^{-3}$  to  $10^{15} \text{ cm}^{-3}$ , wherein the  $n^+$  cathode (K) of the PIN photodiode is incorporated into the second layer (9);wherein, in lateral direction, p regions (20, 21) delineate the second n epitaxial layer (9), and in addition to the anode terminals (A1, A2), a further anode contact area (A3) of the PIN diode is provided at the back side (31).
2. The PIN photodiode of claim 1, wherein buried  $p^+$  layers (22, 23) extending into the p epitaxial layer 10 are located below the p regions (20, 21) which border the second n epitaxial layer (9) in the lateral direction.
3. The PIN photodiode of claim 1, wherein at least within the further anode contact area, acting as a back side anode (A3, 31), a silicon wafer bearing the photodiode is thinned.
4. The PIN photodiode of claim 1 or 3, wherein the anode of the PIN photodiode is electrically contacted from the frontside (30) only.
5. The PIN photodiode of claim 4, wherein one or more anode terminals are formed by deep trench contacts.
6. The PIN photodiode of claim 1, wherein the slightly doped  $n^-$  epitaxial layer (9) has a dopant concentration of approximately  $10^{14} \text{ cm}^{-3}$ .
7. The PIN photodiode of claim 1, wherein the dopant concentration of the first epitaxial layer (10) is substantially  $10^{+13} \text{ cm}^{-3}$ .

8. The PIN photodiode of claim 1, wherein the p regions (20, 21) are configured as p wells in a vertical section.
9. The PIN photodiode of claim 8, wherein the wells extend to the first layer (10), in particular directly to the buried layer (23; 22).
10. The PIN photodiode of claim 1, wherein a dopant concentration of the second layer (9) is less than a dopant concentration of an n region (25) in the second layer, wherein the region (25) forms the collector doping for contacting a cathode (K).
11. The PIN photodiode of claim 1, wherein within and spaced apart from the p regions (20, 21), a cathode region (K, 25) is provided.
12. A method for forming a monolithically integrated vertical PIN photodiode according to a biCMOS technology, wherein
  - (i) a p<sup>+</sup> silicon wafer (11) having a p<sup>-</sup> epitaxial layer (10) with a maximum thickness of substantially 15µm and having a dopant concentration of approximately 10<sup>13</sup> cm<sup>-3</sup> is used as base material;
  - (ii) after a subsequent implementation of a buried layer (22, 23) a (standard) following n epitaxial layer (9) having a dopant concentration within a range of approximately 10<sup>14</sup> cm<sup>-3</sup> is deposited or incorporated;
  - (iii) thereafter, n and p wells (20, 21, 25) are formed and standard following process steps of the technology are performed, wherein in the n- epitaxial layer (9) an n+ cathode of the PIN photodiode is incorporated, and (laterally) in lateral direction p regions (20, 21) delineate the n epitaxial layer (9) and wherein in addition to (said) anode terminals (A1, A2) via the p regions (20, 21) of the planar topside (30) a further anode contact area (A3) is formed on the back side (31).
13. The method of claim 12, wherein finally the silicon wafer at least within the area of the PIN diode is thinned at the back side with a protective covering formed on the front side.

14. The method of claim 12, wherein the anode contact area of the back side is not particularly formed and is not electrically contacted.

15. The method of claim 12, wherein the back side anode (A3) of a chip provided after dicing of the substrate can electrically be contacted by attaching the chip to a lead frame or a conductive area of a wiring board by means of a conductive adhesive, if the serial resistance is not sufficient.

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20. **A monolithically integrated vertical PIN photodiode** formed in biCMOS technology, characterized in that an i-zone of the PIN diode is formed by the combination of a slightly doped  $p^-$  epitaxial layer having a thickness up to substantially  $15\mu\text{m}$  with a dopant concentration of less than  $5 \cdot 10^{14} \text{ cm}^{-3}$  and being located on a highly doped  $p^+$  substrate, with a slightly doped  $n^-$  epitaxial layer formed adjacent to the  $p^-$  epitaxial layer and having a dopant concentration in the range of approximately  $10^{14} \text{ cm}^{-3}$  (range of dopant concentration  $\leq 10^{14} \text{ cm}^{-3}$  to  $< 10^{15} \text{ cm}^{-3}$ ), into which the  $n^+$  cathode of the PIN photodiode is incorporated, wherein p regions laterally delineate the n epitaxial layer in lateral direction and wherein in addition to the anode terminals a further anode contact area of the PIN diode is provided at the back side via the p well regions of the planar front side.

21. The monolithically integrated vertical PIN photodiode of claim 20, wherein the range of dopant concentration is approximately  $10^{13} \text{ cm}^{-3}$ .

22. The monolithically integrated vertical PIN photodiode of claim 16, characterized in that buried  $p^+$  layers extending into the p epitaxial layer are located below the p regions, which laterally delineate the n epitaxial layer in lateral direction.

23. The monolithically integrated vertical PIN photodiode of claim 16, characterized in that at least within the back side anode, the silicon wafer is thinned.

24. The monolithically integrated vertical PIN photodiode of claim 16, characterized in that the anode of the PIN photodiode is electrically contacted from the front side only.
- 5 25. The monolithically integrated vertical PIN photodiode of claim 20, wherein one or more anode terminals are formed by deep trench contacts.
26. **A method of forming** a monolithically integrated vertical PIN photodiode in biCMOS technology, characterized in that
- 10 (i) a p<sup>+</sup> silicon wafer having formed thereon a p<sup>-</sup> epitaxial layer with a thickness of approximately 15μm and having a dopant concentration of approximately 10<sup>13</sup> cm<sup>-3</sup> is used as an initial material,
- (ii) after the subsequent implementation of the buried layer, the n epitaxial layer subsequently formed according to a standard process
- 15 flow is deposited with a dopant concentration in the range of approximately 10<sup>14</sup> cm<sup>-3</sup>,
- (iii) thereafter, the n and p wells are formed and all further standard subsequent process steps of the technology are performed, wherein the n<sup>+</sup> cathode of the PIN photodiode is incorporated into the n<sup>-</sup>
- 20 epitaxial layer, wherein in lateral direction p regions laterally delineate the n epitaxial layer and wherein in addition to anode terminals, a further anode contact area of the PIN diode is formed on the back side via the p well regions of the planar front side such that said further anode contact area of the chip obtained after the dicing of the
- 25 substrate can be contacted by attaching the chip to a lead frame or a conductive area of a wiring board by means of a conductive adhesive, if the serial resistance is not sufficiently small.
27. The method of claim 22, characterized in that in a final step the silicon wafer is thinned at the back side at least within the PIN diode with the front side being covered by a protective covering.
- 30 28. The method of claim 22, characterized in that the anode contact area on the back side is not particularly formed and is not electrically contacted.

## LEGEND OF THE DRAWINGS

Table 1

Optical Wavelength

Quantum Efficiency

Sensitivity

Rise Time

Fall Time

Bandwidth

Capacitance